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## **Rare B Decays and Time Dependent Mixing at CDF**

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## Rare $B$ Decays and Time Dependent Mixing at CDF<sup>†</sup>

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### Abstract

We report recent results on rare  $B$  decay searches – specifically, the decay modes  $B^0 \rightarrow \mu^+ \mu^-$ ,  $B^0 \rightarrow \mu^+ \mu^- K^{0*}$ , and  $B^\pm \rightarrow \mu^+ \mu^- K^\pm$  – from the CDF collaboration using data from the 1992-1993 run of the Tevatron collider. In addition, we present the first CDF measurement of time dependent  $B^0 - \bar{B}^0$  mixing.

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<sup>†</sup> Invited talk given at the XXX<sup>th</sup> Rencontres de Moriond, Les Arcs, March 1995.

# 1 Introduction

Since its discovery more than 15 years ago, the  $b$  system has yielded many surprises, with long lifetimes and large mixing being two of the most prominent. However, in spite of intense scrutiny, the heavy flavour sector remains the source of the largest uncertainty on our knowledge of the CKM mixing matrix which links the mass and the weak eigenstates in the Standard Model (SM). It is conceivable that there are new discoveries in store, and the large  $b$  production cross section in hadron collisions makes hadron colliders competitive for these studies. Thus, the physics of heavy quark systems, and specifically the  $b$  system, has become a burgeoning field of study at hadron colliders.

In just a few years, the CDF experiment running at the Tevatron Collider has addressed many important physics topics in the  $b$  sector, including observation of exclusive  $B$  decay modes [1], measurements of  $B$  lifetimes, both inclusive [2] and exclusive [3], searches for new states such as the  $B_s$  and  $\Lambda_b$  [4], measurement of the  $b$  production cross section [5], and measurement of  $B^0 - \bar{B}^0$  mixing [6]. In this forum it is clearly impossible to do justice to the current status of all these analyses; instead, I will concentrate on the search for rare  $B$  decays and the first CDF measurement of time dependent  $B^0 - \bar{B}^0$  mixing. In both cases I report preliminary results from the 1992-1993 run of the Tevatron, when CDF collected a total of  $19 \text{ pb}^{-1}$  of data. In addition, I have chosen to skip over many of the details of the experimental cuts; these may be found in the references. A detailed description of the CDF detector can be found elsewhere [7] as well.

## 2 Rare $B$ Decays

The study of  $B$  decays provides a testing ground for QCD as well as a window onto the CKM matrix elements  $V_{ij}$ . In particular, while the four “upper-left-hand” elements of this matrix ( $V_{ud}$ ,  $V_{us}$ ,  $V_{cd}$  and  $V_{cs}$ ) are all known to a relative precision of a few percent, the remaining five elements involving the  $b$  and  $t$  quarks are quite poorly known (with the exception of  $V_{tb}$ , known only indirectly by the assumption of unitarity of the matrix). It is exactly these elements that can be accessed by studying  $B$  decays, either directly ( $V_{ub}$  and  $V_{cb}$ ) or indirectly through virtual loop processes ( $V_{td}$ ,  $V_{ts}$ , and  $V_{tb}$ ). Examples of these processes are  $B^0 - \bar{B}^0$  mixing and the decay modes  $B^0 \rightarrow \mu^+ \mu^-$ ,  $b \rightarrow (s, d) + \gamma$  (“penguins”), and  $b \rightarrow (s, d) + \ell^+ \ell^-$ , all of which are flavour-changing neutral currents (FCNC). For an extensive discussion of the theoretical aspects of these (and other) FCNC decays in the  $B$  sector, see references [8, 9, 10] and references therein. In all of what follows, references to specific modes include the charge conjugate modes unless specifically noted.

## 2.1 $B_d^0 \rightarrow \mu^+ \mu^-$ and $B_s^0 \rightarrow \mu^+ \mu^-$

These decays are classic flavour-changing neutral current (FCNC) processes, analogous to the decay  $K^0 \rightarrow \mu^+ \mu^-$ , and are thus forbidden by the GIM mechanism at tree level in the Standard Model. At higher order, diagrams such as those in Figure 2.1 come into play. Both decay modes are helicity suppressed, and the SM branching ratios are small:  $\text{BR}(B_d^0 \rightarrow \mu^+ \mu^-) = 8.0 \times 10^{-11}$  and  $\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = 1.8 \times 10^{-9}$  [11]. In extensions to the Standard Model such as a two-Higgs doublet model [12] or models containing lepto-quarks, these branching ratios can be enhanced by orders of magnitude. Alternately, these modes can be used in the context of a very general effective-Lagrangian approach to limit the operator structure of any new physics [13]. Experimentally, the current 90% CL limits are  $\text{BR}(B_d^0 \rightarrow \mu^+ \mu^-) < 5.9 \times 10^{-6}$  from CLEO [14], and an unseparated limit of  $\text{BR}(B_{d,s}^0 \rightarrow \mu^+ \mu^-) < 8.3 \times 10^{-6}$  from UA1 [15].

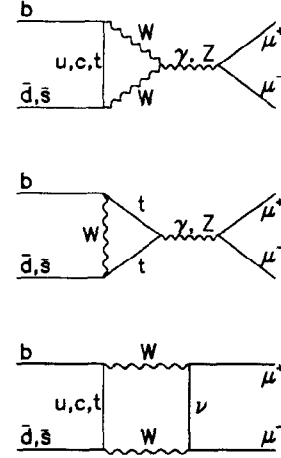


Figure 2.1: Some one-loop Feynman diagrams for  $B^0 \rightarrow \mu^+ \mu^-$  decays.

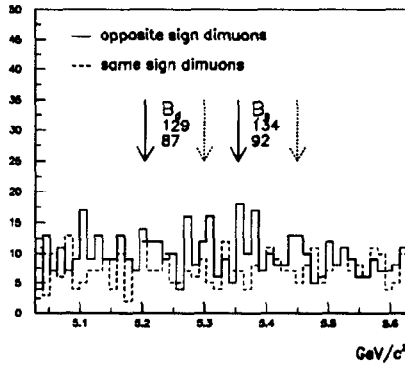


Figure 2.2: The like-sign (dashed) and unlike-sign (solid)  $\mu\mu$  mass spectra after initial cuts. The arrows and numbers of events refer to the  $B_d^0$  and  $B_s^0$  mass windows.

The CDF analysis starts with a di-muon sample with both muons having  $p_T > 1.9$  GeV/c. We keep both unlike-sign and like-sign pairs; the latter is used for background studies. We require that both muons be in the fiducial region of our Silicon Vertex Detector (SVX) [16] where the track reconstruction is most precise. We require that the muon pair (*i.e.*, the  $B$  candidate) have  $p_T > 6$  GeV/c; this rejects more than 90% of our candidates but allows us to correctly normalize our results in a MC-independent fashion to our own measured  $B$  meson production cross section. At this point we are still left with of order 100 events in both the  $B_d^0$  and  $B_s^0$  mass ranges ( $\pm 75$  MeV/c<sup>2</sup> around the measured masses); the  $\mu\mu$  mass spectra are shown in Figure 2.2.

Experience with the Silicon Vertex Detector has shown convincingly [2] that we are able to accurately measure transverse flight distances in order to separate a long-lived  $b$  signal from prompt background. Thus we use a pseudo-lifetime variable defined as:

$$c\tau^* = \frac{L_{xy} \cdot m_{\mu\mu}}{p_T(\mu\mu)}$$

where  $L_{xy}$  is the transverse distance between the primary vertex and the muon-muon vertex,

and  $m_{\mu\mu}$  and  $p_T(\mu\mu)$  are the invariant mass and the transverse momentum respectively of the muon pair. Note that “ $c\tau^*$ ” is not truly the proper lifetime of the  $B^0 \rightarrow \mu^+\mu^-$  candidates because it contains only transverse (and not longitudinal) quantities. We require  $c\tau^* > 100 \mu\text{m}$ . Finally, we look at the isolation  $I$  of the  $B$  candidate, defined as:

$$I = \frac{p_T(B)}{p_T(B) + \sum p_T}$$

where the sum in the denominator is over all other tracks within  $\Delta(R) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 1$  from the  $B$  candidate direction. We require  $I > 0.7$  (i.e., the muon pair accounts for more than  $\sim$ one-half of the observed  $p_T$  in the cone). One of the advantages of using this variable to reduce background is that it is possible to measure *in situ* the efficiency of the cut for real  $B$  mesons from our exclusive  $B^0 \rightarrow J/\psi K^{0*}$  signal, thus avoiding any reliance on MC models of  $B$  production.

After these cuts, we are left with no  $B_d^0 \rightarrow \mu^+\mu^-$  candidates, and 1  $B_s^0 \rightarrow \mu^+\mu^-$  candidate; in the like-sign samples there are 2  $B_d^0$  and no  $B_s^0$  “candidates”. The  $\mu\mu$  mass distributions are shown in Figure 2.3. The overall efficiency and acceptance of our criteria (including the  $p_T$  cut on the  $B$  meson candidate) is  $\sim 2\%$  with the largest uncertainty on this number coming from the statistics of the exclusive  $B$  sample used to measure the efficiency of the isolation cut. Our results (conservatively calculated without performing a background subtraction) are  $\text{BR}(B_d^0 \rightarrow \mu^+\mu^-) < 2.0 \times 10^{-6}$  and  $\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) < 6.8 \times 10^{-6}$ , both at the 90% CL, the best limits to date on these modes.

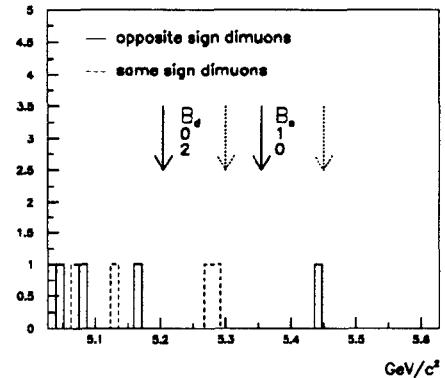


Figure 2.3: As in Figure 2.2, but after all cuts.

## 2.2 $B^+ \rightarrow \mu^+\mu^- K^+$ and $B_d^0 \rightarrow \mu^+\mu^- K^{0*}$

At the quark level, the process  $b \rightarrow s\ell^+\ell^-$  can proceed through a loop diagram similar to a penguin process, with the radiated boson ( $\gamma$  or  $Z^0$ ) coupling to lepton pairs. As well as these so-called “electroweak penguins”, there are box diagrams containing two  $W$ ’s which exchange a neutrino. At the meson level, there are – in addition to these “short distance” loop effects – “long distance” contributions from the exclusive decays  $B \rightarrow \psi^{(\prime)} K^{(*)}$  with  $\psi^{(\prime)} \rightarrow \ell^+\ell^-$ , and interference between the two processes. An important point that has been raised by a number of authors [10, 17] is that the dilepton mass spectrum in this decay is an important observable: at low dilepton masses, the dominant Standard Model diagram is from a virtual  $\gamma$  and the rate can be related to the  $b \rightarrow s\gamma$  decay. At larger dilepton masses the  $Z$  and box diagrams become relatively more important, and there are potential contributions from non-SM heavy particles.

CLEO has currently set (preliminary) 90% CL limits of  $\text{BR}(B^+ \rightarrow \mu^+ \mu^- K^+) < 0.90 \times 10^{-5}$  and  $\text{BR}(B_d^0 \rightarrow \mu^+ \mu^- K^{0*}) < 3.10 \times 10^{-5}$  (using the entire dilepton mass range except the  $\psi^{(l)}$  region) [10], to be compared to SM predictions of  $6.0 \times 10^{-6}$  and  $2.9 \times 10^{-6}$  respectively [8]. These modes are well-suited to searches at hadron colliders, where the dilepton final states provide a clean signature, and CDF is quite competitive here.

Our analysis [18] again starts with a dilepton sample, with both muons having  $p_T \geq 2.0$  GeV/c and at least one having  $p_T \geq 2.8$  GeV/c. We require that the di-muon effective mass be between 2.8 GeV/c<sup>2</sup> and 4.5 GeV/c<sup>2</sup>. A secondary vertex is reconstructed from the three (in the case of  $B^+ \rightarrow \mu^+ \mu^- K^+$ ) or four ( $B_d^0 \rightarrow \mu^+ \mu^- K^{0*}$ ,  $K^{0*} \rightarrow K^+ \pi^-$ ) charged particles, and a cut of  $c\tau^* \geq 100$   $\mu\text{m}$  is applied. We again require that the  $B$  candidate system be isolated, with  $I > 0.7$ .

The final  $\mu\mu X_s$  and  $\mu\mu$  mass distributions, where  $X_s$  is either  $K^+$  or  $K^{0*}$  are then used to calculate the number of  $B \rightarrow J/\psi X_s$  events and the number of  $B \rightarrow \mu^+ \mu^- X_s$  candidates. In particular, the di-muon mass ranges from 3.3 to 3.6 GeV/c<sup>2</sup> and 3.8 to 4.5 GeV/c<sup>2</sup> are used for the rare decays. The final  $\mu\mu X_s$  mass distributions contain a few events per bin in the  $B$  mass range, when the  $\mu\mu$  mass is required to be in the region quoted above; these numbers are consistent with background estimates as measured from the  $B$  sidebands; ie, from events giving  $\mu\mu X_s$  masses outside of the  $B$  mass region. An example for the  $B^+ \rightarrow \mu^+ \mu^- K^+$  channel is shown in Figure 2.4.

From the expected number of background events, the number of observed  $B \rightarrow \mu^+ \mu^- X_s$  candidates, the number of observed  $B \rightarrow J/\psi K^{(*)}$  decays, and the measured branching ratio for  $B \rightarrow J/\psi K^{(*)}$ , we can calculate an upper limit for the absolute branching ratio  $\text{BR}(B \rightarrow \mu^+ \mu^- X_s)$  for the  $\mu\mu$  mass range used. Those numbers are (at the 90% CL):  $\text{BR}(B^+ \rightarrow \mu^+ \mu^- K^+ (\text{partial})) < 0.8 \times 10^{-5}$ , and  $\text{BR}(B_d^0 \rightarrow \mu^+ \mu^- K^{0*} (\text{partial})) < 1.3 \times 10^{-5}$ .

In the context of the Standard Model, these partial branching ratios can be related to the total branching ratios for  $B^+ \rightarrow \mu^+ \mu^- K^+$  and  $B_d^0 \rightarrow \mu^+ \mu^- K^{0*}$  (i.e., for the entire di-muon mass range) through the use of heavy quark effective theory [19]. We obtain:  $\text{BR}(B^+ \rightarrow \mu^+ \mu^- K^+) < 3.5 \times 10^{-5}$ , and  $\text{BR}(B_d^0 \rightarrow \mu^+ \mu^- K^{0*}) < 5.1 \times 10^{-5}$ , at the 90% CL.

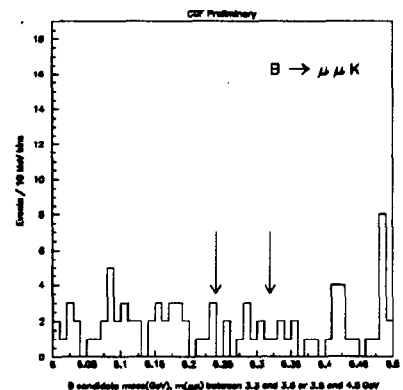


Figure 2.4:  $\mu\mu K$  mass distribution after requiring that the  $\mu\mu$  mass be in the range 3.6 to 3.8 GeV/c<sup>2</sup> or 3.8 to 4.5 GeV/c<sup>2</sup>. The arrows indicate the  $B$  signal region, where no excess is apparent.

## 2.3 Penguin Decays

The importance of studying so-called “penguin” decays such as  $b \rightarrow s\gamma$  has been stressed by a number of authors; experimentally, the CLEO collaboration has observed the decay  $B \rightarrow K^*\gamma$  and calculated the branching ratio to be  $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$  [10]. As for other FCNC  $B$  decays, penguin decays provide sensitivity, through loop effects, to both SM parameters (for example, the  $b \rightarrow s\gamma$  to  $b \rightarrow d\gamma$  ratio can be used to access the ratio  $\frac{|V_{ts}|}{|V_{td}|}$ ) and new (non-SM) effects.

Currently, this decay is extremely difficult to study at hadron colliders due to the lack of a straight-forward trigger signature; the obvious handle, namely the energetic  $\gamma$ , is swamped by QCD processes. CDF is currently implementing a special penguin trigger that uses the full power of the programmable Level 2 trigger processors to require a photon cluster and two stiff tracks ( $p_T \gtrsim 2$  GeV/c). The offline analysis will use topological criteria, a  $c\tau^*$  cut, isolation, and effective mass criteria to search for a  $B \rightarrow K^*\gamma$  signal. We expect to have a handful of events per 100 pb $^{-1}$ , and thus a measurable signal in the 1995 data.

## 3 Time Dependent Mixing from CDF

$B$  mixing is also a FCNC process, mediated in the Standard Model by box diagrams and thus sensitive to both CKM elements and the top quark mass. It is well established that mixing is large in the  $B$  sector, and it has been measured by a number of experiments at both  $e^+e^-$  machines and hadron colliders. Physically, the goal is to measure the mixing parameter  $x$  ( $= \Delta m/\Gamma$ ) for both  $B_d^0$  and  $B_s^0$ . However,  $x_s$  is large – the SM prediction is  $x_s \sim 20$  [20], and the current experimental limit is  $x_s > 8.5$  [21] – so the  $B_s^0$  mixes rapidly and the oscillations are experimentally difficult to observe.

In the past, CDF has measured the time-integrated mixing by studying the ratio of the number of like-sign dilepton pairs to opposite-sign dilepton pairs. With the large data sample from Run 1A and the precision of the SVX, we are now able to attack time-dependent measurements as well. We use a dimuon sample (two muons with  $p_T > 2$  GeV/c) and reconstruct a tertiary (“charm”) vertex from tracks not consistent with the primary vertex (see Figure 3.1 for a schematic view of such an event). We require that the charm vertex be well-reconstructed and that the effective mass of the  $\mu$ +“charm” system be less than 5 GeV/c $^2$ . The transverse momentum of the muon relative to the charm system ( $p_T^{\text{rel}}$ ) is then used to enrich the sample in  $b$  decays and to measure the  $c\bar{c}$  fraction of the sample. With a cut of  $p_T^{\text{rel}} \geq 1.3$  GeV/c, the



charm background is very small:  $(0.7 \pm 0.5)\%$ . After this cut, we are left with 1516 same-sign muon events, and 2357 opposite-sign events. The remaining background, evaluated using the “away” side muon impact parameter distribution, is found to be  $\sim 12\%$ ; we estimate that 84% (71%) of the muons on the vertex tag side (away side) are from direct  $B$  decays.

The sign of the primary (charm-associated) muon provides a flavour tag while the second muon gives the second flavour tag. The mixing parameter can thus be extracted from the fraction of like-sign dimuons. This ratio, as a function of  $c\tau^*$  on the vertex tag side, is then fit to extract the mixing parameter  $x_d$ . The data are shown in Figure 3.2, together with 3 curves. In all fits, we constrain the fraction of  $B_d$  and  $B_s$  to the measured LEP values of  $0.37 \pm 0.03$  and  $0.15 \pm 0.04$  respectively, and constrain the  $B$  lifetime to our own measured value. The  $c\tau^*$  resolution is taken from MC, as is the fraction of sequential  $b \rightarrow cX, c \rightarrow \ell s\nu$  decays. The only free fit parameter is  $x_d$ .

Figure 3.2 shows the results of three different cases. In the first (dotted line), both  $x_d$  and  $x_s$  are constrained to be zero (no mixing). Thus, this curve shows the effect of sequential  $B$  decays and background in the sample. The second case (dashed line) has  $x_d$  set to zero but maximal  $B_s$  mixing ( $x_s \gg 1$ ). The confidence level for this case is less than 5% indicating that we are observing the effects of  $B_d$  mixing. The final case (solid line) is the result of a binned  $\chi^2$  fit allowing  $x_d$  to float; the result is  $x_d = 0.64 \pm 0.18$  (stat)  $\pm 0.21$  (sys), where the dominant systematic uncertainty arises from the modeling of the sequential decay fraction.

## 4 Conclusions

I have presented some recent preliminary CDF results on the FCNC processes of rare  $B$  decays and time dependent  $B - \bar{B}$  mixing, using the 1992-1993 data sample of approximately  $19 \text{ pb}^{-1}$ . CDF is currently taking data and should accumulate an additional  $\sim 100 \text{ pb}^{-1}$  by the end of 1995. Coupled with new triggers, we expect this data to dramatically improve our sensitivity in all areas of  $B$  studies.

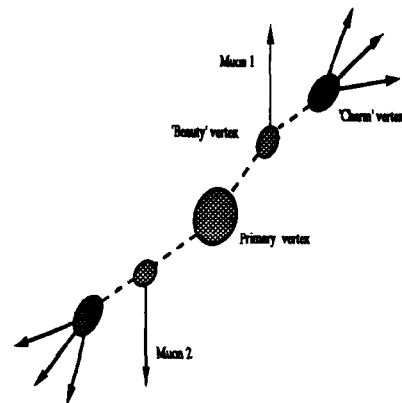


Figure 3.1: Schematic view of the mixing analysis technique with the dimuon sample.

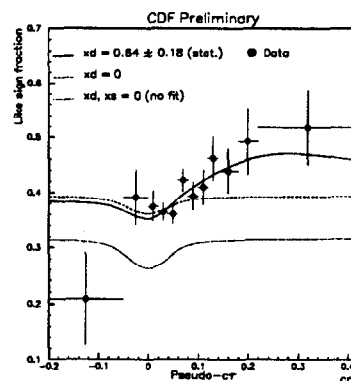


Figure 3.2: The like-sign dimuon fraction as a function of  $c\tau^*$ . The three curves are explained in the text.

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